AFRL-ML-TY-TR-2006-4515

AN ALTERNATIVE TO EPA METHOD 9 - FIELD VALIDATION OF THE DIGITAL OPACITY COMPLIANCE SYSTEM (DOCS):
RESULTS FROM THE ONE-YEAR REGULATORY STUDY

Steven Rasmussen and Daniel A. Stone
75 CEG/CEV, 7274 Wardleigh Road
Hill AFB, UT 84056-5137

Joseph D. Wander
AFRL/MLQL, 139 Barnes Drive
Tyndall AFB, FL 32403-5323

Michael J. McFarland
Dept. of Civil and Environmental Engineering
Utah State University, 1405 Mount Logan Drive
Logan, UT 84321

August 2005

Final Report (Supplemental) to ESTCP

DISTRIBUTION STATEMENT A:

Approved for public release; distribution unlimited.

Air Force Research Laboratory
Materials and Manufacturing Directorate
Airbase Technologies Division
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403-5323

NOTICE

This technical report is approved for publication.

/s/

JOSEPH D. WANDER, PhD
Work Unit Manager

/s/

SANDRA R. MEEKER
Chief, Airbase Sciences Branch

/s/

JIMMY L. POLLARD, Colonel, USAF
Chief, Airbase Technologies Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 15-01-2006

2. REPORT TYPE: Final Technical Report

3. DATES COVERED *(From - To)*: 01-01-2004 - 31-12-2004

4. TITLE AND SUBTITLE
An Alternative to EPA Method 9 - Field Validation of the Digital Opacity Compliance System (DOCS): Results from the One-Year Regulatory Pilot Study

5a. CONTRACT NUMBER: F42650-03-D-0007

5b. GRANT NUMBER:

5c. PROGRAM ELEMENT NUMBER: 63716D

5d. PROJECT NUMBER: 6905

5e. TASK NUMBER: L40B

5f. WORK UNIT NUMBER: 6905L40B

6. AUTHOR(S)
Micah Yairi, Steve L. Rasmussen, Daniel A. Stone, Joseph D. Wander, Michael J. McFarland

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
75 CEG/CEV
7425 Wardleigh Road
Hill AFB, UT 84056-5137

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Materials and Manufacturing Directorate
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403-5323

10. SPONSOR/MONITOR'S ACRONYM(S): MLQD

11. SPONSOR/MONITOR'S REPORT NUMBER(S): AFRL-ML-TY-TR-2006-4515

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Technical monitor: Dr. Joe Wander, AFRL/MLQL, 850-283-6240 (DSN 523-6240)

14. ABSTRACT
The US Environmental Protection Agency's (EPA) Emission Measurement Center (EMC), in conjunction with EPA Regions VI and VIII, the State of Utah and the US Department of Defense (DoD), has conducted a series of long-term pilot and field tests to determine the accuracy and reliability of a visible opacity monitoring system consisting of a conventional digital camera and a separate computer software application for plume opacity determination. This technology, known as the Digital Opacity Compliance System (DOCS), has been successfully demonstrated at EPA-sponsored Method-9 "smoke schools" as well as at a number of government and commercially operated industrial facilities. Results from the current DOCS regulatory pilot study demonstrate that, under regulatory enforcement conditions, the average difference in opacity measurement between the DOCS technology and EPA Reference between the DOCS technology and EPA Reference Method 9 (Method 9) is 1.12%. This opacity [Continued on p. ii]

15. SUBJECT TERMS
Air pollution control; emissions monitoring; digital camera; visible opacity; CEM; EPA Method 9

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	U	37	Dr Joseph Wander

19b. TELEPHONE NUMBER *(Include area code)*: 850-283-6240

13. ABSTRACT (CONTINUED)

difference, which was computed from the evaluation of 241 regulated air sources, was found to be statistically significant at the 99% confidence level. In evaluating only those sources for which a nonzero visible opacity level was recorded, the average difference in opacity measurement between the DOCS technology and EPA Reference Method 9 (Method 9) was 1.20%. However, in this case, the opacity difference was found to be not significant at the 99% confidence level, a finding that suggests that the two opacity measurement methods are statistically equivalent when measuring nonzero visible opacity emissions.

The EMC has acknowledged the acute need for the development and promulgation of a new, scientifically defensible method for the measurement of visible opacity. The use of digital imaging/processing brings current technology to bear on this important regulatory issue. Digital technology offers increased accuracy, a permanent record of measurement events, lower costs and a scientifically defensible approach for opacity determination. Based on its successful deployment under regulatory enforcement conditions, EMC in conjunction with the DoD has developed a draft camera-based visible opacity measurement method, which has been posted on the EPA website and is currently undergoing public comment.

EXECUTIVE SUMMARY

A. OBJECTIVE: The objective of this long-term pilot and field exercise was to determine the accuracy and reliability of a visible opacity monitoring system consisting of a conventional digital camera and a separate computer software application for plume opacity determination under conditions relevant to regulatory applications.

B. BACKGROUND: An expansive body of evidence implicates ultrafine particles, particularly those generated in the course of ordinary combustion processes, as significant sources of human disease and environmental degradation. As an early regulatory step, the US Environmental Protection Agency (EPA) developed a visible opacity method (Method 9) to estimate the rate of emission of soot and related combustion fines exhausting from a stack. Smoke readers requalify twice annually at EPA-sponsored Method-9 "smoke schools," which is expensive and interrupts manpower availability, and their observations are inescapably subjective and unverifiable. EPA's Emission Measurement Center (EMC) has acknowledged the acute need for the development and promulgation of a new, scientifically defensible method for the measurement of visible opacity. The initial phases of this program developed the Digital Opacity Compliance System (DOCS) and validated that the combination of digital camera and software tested is a reliable tool for measuring plume opacities under conditions specified for Method 9.

C. SCOPE: This report details and interprets results from a series of long-term pilot and field tests at a number of government and commercially operated industrial facilities in conjunction with the EMC, EPA Regions VI and VIII, the State of Utah and the US Department of Defense (DoD) The report compares results generated by digital cameras paired with DOCS against concurrent measurements reported by Method-9-qualified smoke readers and/or by the standard transmissometer incorporated into the smoke generator.

D. METHODOLOGY: Smoke generation was accomplished by spraying oil droplets onto a heated plate. "True" opacity was read across the chimney by a digital transmissometer. Smoke readers estimated the opacity of the plume visually, following EPA Method 9. The digital cameras were mounted on tripods and focused, after which images were recorded by manually pressing the shutter. Digital opacity was measured with the DOCS software by drawing a box around a segment of the plume 1-2 stack diameters above the stack and projecting 1-2 plume diameters to either side of the plume. The DOCS software compared the image density of the plume to that of the background defined on either side to calculate the plume opacity.

E. TEST DESCRIPTION: Cameras and smoke readers were positioned between the Sun and the stack to be read, and readings were made simultaneously as specified by Method 9. This procedure was repeated in several military and industrial locations that are subject to regulation. For each set of tests the results from the DOCS method were compared in pairs with those from the reader and/or from the transmissometer.

F. RESULTS: For opacity values of 5-40 %---the region of regulatory interest---the DOCS software operated with two of the newer camera models gave readings that were slightly more precise and slightly lower on average than the readers, and statistical analysis showed each camera gave results equivalent--at a 99% confidence level--to those reported by the readers. Results from a third model of digital camera were close, but determined by analysis not to be statistically equivalent at a 99% confidence level to the readers.

G. CONCLUSIONS: The main demonstration showed the original (now obsolete) camera operated with DOCS software gave readings statistically equivalent to those reported by trained readers. This extension to include two newer commercial digital cameras, respectively paired with the same software, established that the method is general for any camera after it has been shown to produce equivalent results by a comparison of this sort.

H. RECOMMENDATIONS: Digital technology offers increased accuracy, a permanent record of measurement events, lower costs and a scientifically defensible approach for opacity determination. Based on its successful deployment under regulatory enforcement conditions, EMC in conjunction with the DoD has developed a draft camera-based visible opacity measurement method, which has been posted on the EPA website and is currently undergoing public comment.

Table of Contents

List of Figures

List of Tables

List of Acronyms

ABW	Air Base Wing
AFB	Air Force Base
AFRL	Air Force Research Laboratory
CEM	Continuous emissions monitor
CD	Compact disc
COTS	Commercial off-the-shelf
COM	Continuous opacity monitor
DC290	Kodak model DC290 digital camera
DOCS	Digital Optical Compliance System
DoD	Department of Defense
DQA	Data Quality Assessment
DQO	Data Quality Objective
EMC	EPA Emissions Measurement Center
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
ETA	Eastern Technical Associates
Method 9	40 CFR 60, Appendix A, Method 9, *Visual Determination of Opacity from Stationary Sources*
NASA	National Aeronautics and Space Administration
OAQPS	Office of Air Quality Performance Standards
OO-ALC	Ogden Air Logistics Center
RPS	Regulatory pilot study
RTAP	Regulatory and Technical Advisory Panel
US	United States
40 CFR	Section 40 of the Code of Federal Regulations

1.0 INTRODUCTION

Most United States (US) Department of Defense (DoD) installations/facilities are subject to Title V of the 1990 Clean Air Act Amendments (CAAA). While a variety of air sources are regulated under Title V, the most common are those that generate visible emissions[1]. To demonstrate compliance with federal visible emission limits, the opacity associated with regulated air sources must be verified through use of an approved regulatory method.

For the majority of regulated air sources, the primary method for determining compliance with permitted opacity levels is the US Environmental Protection Agency's (EPA) Reference Method 9 (Method 9)[2]. Method 9 relies on trained human observers to visually determine compliance by measuring the opacity of a smoke plume once every 15 seconds for a specified time period (Table 1). The 15-second opacity recordings are averaged to determine a single opacity measurement that is then compared against the facility's permitted opacity level.

To become legally certified as a Method 9 visual opacity observer, an individual must complete classroom training and successfully pass a visual opacity field examination conducted at an EPA-approved smoke school once every six months. The field examination requires that the Method 9 candidate determine the visible opacity of 25 white and 25 black smoke plumes with an error rate of no greater than 15% for any individual opacity observation and an aggregate opacity measurement error rate of no greater than 7.5% for all fifty (50) readings. While Method 9 has an extensive history of successful employment, its opacity measurements are inherently subjective, a characteristic that renders its results vulnerable to claims of inaccuracy, bias and, in some cases, outright fraud.

Beyond the technical concerns associated with the limited accuracy and reliability of Method 9 results, the recurring training costs necessary to support Method 9 certification can become a significant financial burden on a facility's compliance budget. With historically flat and currently declining federal environmental compliance budgets, development of new, cost-effective and regulatorially supportable methods for verifying compliance with permitted visible opacity standards is receiving increased attention by environmental compliance enforcement personnel as well as the regulated community[3].

The Digital Opacity Compliance System (DOCS)—an innovative technology that employs digital imaging technology for quantifying visible opacity—has been developed and field-tested as a technically defensible and economically competitive method to verify compliance with permitted opacity levels[4, 5, 6].

DOCS uses a commercial-off-the-shelf (COTS) digital camera to capture images of visible opacity, which are then downloaded to a standard personal computer and analyzed using specialized computer software. The DOCS technology not only has been advertised as an accurate and reliable alternative technology to Method 9 but it has the added advantage of furnishing the technology user with a permanent visual record of the emissions at the time of the observations.

Table 1. EPA Reference Method 9 Field Procedures for Opacity Measurement of Stationary Air Sources

Positioning

- Observer must stand at a distance sufficient to provide a clear view of the visible emissions
- Observer must have the sun oriented within a 140° sector to the back of the observer
- Observer must ensure that the line of vision is perpendicular to plume flow direction

Recording

- Observer must record name of the facility, emission location, facility type, observer's name and affiliation, and the date on which observations are made.
- Observer must record time, estimated distances to the emission location, approximate wind speed and direction, description of sky conditions and plume background at the time of measurement.

Observations

- Observer must make opacity observations at the point of greatest visible opacity where condensed water vapor is absent.
- Observer must observe plume at 15-second intervals. Observer must not look continuously at the plume.
- Observer must record approximate distance from outlet to point in plume where observations were made.
- Observer must record opacity observations to the nearest 5% opacity at 15-second intervals on an observational record sheet (at least 24 observations must be recorded).

Data Reduction

- Observer shall determine opacity as an average of 24 consecutive observations recorded at 15-second intervals.

2.0 BACKGROUND

The presence of visible air emissions from regulated stationary air sources provides irrefutable evidence that airborne particles are being discharged into the atmosphere[1,7]. Not only has the public expressed its concern regarding the negative psychological effects of visible emissions, but, under many circumstances, particulate emissions have been identified as the cause of increased human health and environmental risk. Due to public concerns regarding the potential health and environmental impacts associated with visible air emissions, current federal statutes as well as many state and local air quality control laws actively regulate the opacity of plumes (*i.e.*, point sources of air pollution).

This technology field demonstration (TFD) was designed to evaluate the technical performance of DOCS under regulatorially enforceable conditions. This study was formulated to complement previous DOCS

field demonstration efforts supported by the Environmental Security Technology Certification Program (ESTCP)*, and it was requested by the EPA's Emission Measurement Center (EMC) (Research Triangle Park, N.C.) to establish the technical basis for a new regulatory method for measuring visible opacity[3,8]. Independent regulatory and technical oversight for the DOCS one-year regulatory pilot demonstration study was provided by the DOCS regulatory and technical advisory panel, which consisted of EPA scientists, engineers and air quality enforcement personnel from Regions VI (Texas) and VIII (Colorado), plus state regulators from California, Texas and Utah. Beyond the regulatory community, DoD air compliance personnel from Elmendorf Air Force Base, Alaska, Fort Hood, Texas, Hill Air Force Base, Utah and Aberdeen Proving Ground, Maryland, participated in the advisory panel's deliberations. Table 2 lists the panel members and their affiliations. The following sections provide a technical description of the DOCS technology. Additional technical details can be found in References 4, 5, 6 and 9.

Table 2. DOCS Regulatory and Technical Advisory Panel (RTAP) Membership

Name	Affiliation
Craig Blackhurst	Hill Air Force Base, Utah: Contractor
John Bosch	EPA Emission Measurement Center, Research Triangle Park, N.C.
Mary Boyer	California Air Resources Board, Sacramento, California
Joanie Cook	Fort Hood, Texas
Gordon Esplin	Genesis Engineering, Vancouver, British Columbia
John Frohning	HMH Consulting, Anchorage, Alaska
Ross Gleason	Elmendorf Air Force Base, Alaska
Josh Gunter	Hill Air Force Base, Utah: Contractor
Erik Haas	HMH Consulting, Anchorage, Alaska
James Jensen	Hill Air Force Base, Utah; Contractor
Robert Kennedy	Fort Hood, Texas
Dennis Korycinski	Elmendorf Air Force Base, Alaska
Paul Hopp	Aberdeen Proving Ground, Maryland
Thomas Logan	EPA Emission Measurement Center, Research Triangle Park, N.C.
Ray Magyar	EPA Region VI (Dallas, Texas)
Bob Mann	Texas Commission of Environmental Quality (TCEQ), Austin, Texas
Mike McFarland	Utah State University, Logan, Utah
Jay Morris	Utah Division of Air Quality (UDAQ)
Glenn Palmer	Hill Air Force Base, Utah
Scott Peters	Hill Air Force Base, Utah; Contractor
Steve Rasmussen	Hill Air Force Base, Utah
Guillermo Reyes	Texas Commission of Environmental Quality (TCEQ), Austin, Texas
Ron Rutherford	EPA Region VIII (Denver, Colorado)
John Smith	Texas Commission of Environmental Quality (TCEQ), Austin, Texas
Mike Spencer	Eastman Kodak, Inc., Rochester, N.Y.
Dan Stone	Hill Air Force Base, Utah
Mark Tavianini	California Air Resources Board, Sacramento, California
Larry Webber	Army Environmental Center, Aberdeen Proving Ground, Maryland

*Environmental Security Technology Certification Program. ESTCP's goal is to demonstrate and validate promising, innovative technologies that target the Department of Defense's (DoD's) most urgent environmental needs through their implementation and commercialization.

2.1 Basic Theory of the DOCS Technology

During the application of the DOCS technology, digital photographs of visible emissions are taken from positions that allow the plume to be clearly viewed against a sky background. These photographs are downloaded to a laptop or desktop computer, with which they can be analyzed for opacity using the DOCS software. The initial steps in analyzing the digital image for opacity include: 1) activating the DOCS opacity analysis program, 2) retrieving those digital photographs that are to be evaluated and 3) using the DOCS program to draw an analysis box (or grid) around that portion of the visible emissions that will be analyzed for opacity (Figure 1).

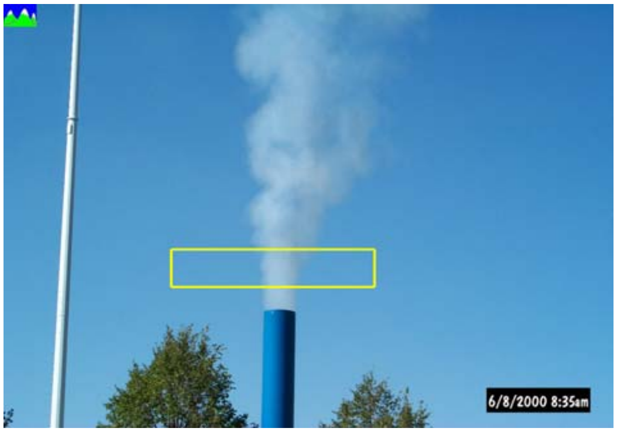

Figure 1. Drawing of the Opacity Analysis Box Using the DOCS Technology

After selection of the analysis box, the DOCS software first distinguishes whether the plume is lighter or darker than the background, by simply transforming the image into a gray scale with enhanced dark and light colors. By assuming that the spatial color intensity of the pixels located at the vertical edges of the analysis box correspond to background and those located in the center represent visible emissions, the software is able to determine statistically whether the emissions are lighter or darker than the background.

Once the contrast between the emissions and background has been established, the DOCS software transforms the spatial color intensity data (which are stored in image files) into an optical space characterized by the dimensions of hue, saturation and value (HSV). In HSV space, the DOCS software employs a principal component analysis (PCA) approach to identify the most important parameter gradient (*i.e.*, the parameter gradient that exhibits the maximum variability in color intensity). That parameter (or principal component) is then used to establish a linear scale of opacity, from which an overall aggregate opacity of the plume can be determined[9].

2.2 *Practical Application of the DOCS Technology*

Under normal circumstances, the DOCS user rarely needs to understand the complex mathematical relationships associated with digital image transformation. Rather, the user simply draws an analysis box around the area of the plume to be analyzed for opacity. The DOCS software then establishes the plume background based on spectral information contained in the pixels. The size and shape of the analysis box, which is controlled by the user of the DOCS software, must be chosen judiciously, because the final

opacity measurement will ultimately depend on what part of the image the DOCS software identifies as background.

2.3 *Results from the ESTCP-sponsored DOCS Technology Field Demonstration (TFD)*

From January 2001 through December 2003, a DOCS TFD study sponsored by ESTCP (project CP-200119) was conducted in which the DOCS measurement technology was evaluated both at EPA-approved Method 9 smoke schools and at DoD industrial and private commercial facilities[3,4,5,6,8]. Results from this TFD, conducted at EPA-approved smoke schools—located, respectively, in Ogden, Utah, Augusta, Georgia, and Columbus, Ohio—confirmed that, under fair weather conditions (*e.g*., clear sky conditions), the DOCS technology consistently met the quantitative performance standards for accuracy and reliability established for Method 9. Furthermore, over the opacity ranges of regulatory importance (*i.e*., 0 to 40% opacity), the accuracy of DOCS was demonstrated to be statistically better than that achieved by Method-9-certified human observers.

Under adverse weather conditions (*e.g*., dark overcast skies), the accuracy of both the DOCS technology and Method-9-certified human opacity readers in measuring visible opacity was diminished. However, under all weather conditions, the variability in the DOCS opacity measurements was statistically *less* than that reported by Method-9-certified observers, a fact that further supports the assertion that the DOCS technology is consistently more reliable than Method 9.

During limited deployment of the DOCS technology at DoD industrial and private commercial facilities, DOCS's accuracy in measuring visual opacity was found not only to be comparable to Method-9-certified human observers but to exhibit several important practical advantages for DoD facilities: 1) improved measurement objectivity and reliability, 2) lower deployment and maintenance costs and 3) generation of a permanent digital image of visible opacity that can be easily referenced in resolving regulatory enforcement actions.

Economic analysis of the DOCS technology illustrated that stateside and remotely located DoD facilities could recognize an estimated *annual* cost savings of $9,000 and $15,650, respectively, *per pair* of trained DOCS technology users replaced. As DoD currently certifies over 3,400 individuals trained in Method 9, DoD-wide adoption of DOCS could save the DoD in excess of $15.3M *annually* in compliance costs. With these potential cost savings, the payback period for investment in the DOCS technology is *less* than one year. A net present value (NPV) analysis of life-cycle cost savings demonstrated that DoD facilities located stateside and remotely could save approximately $40,000 and $70,000, respectively, per pair of trained DOCS technology users. These costs savings translate to a potential aggregate financial benefit to DoD estimated to be at least $68.2M over the (assumed) five-year life cycle of the DOCS equipment[3,8].

After a comprehensive technical review of results from the ESTCP-sponsored DOCS TFD, and in light of continuous appeals by EPA regional offices, state regulatory agencies and the regulated community for the establishment of a camera-based visible opacity field measurement method, EMC recommended the development and implementation of a one-year regulatory pilot study (RPS) in which the accuracy and reliability of the DOCS technology would be evaluated side-by-side with Method-9-certified human observers under regulatory enforcement conditions. This one-year RPS demonstration was designed to collect DOCS technology performance data during air quality enforcement inspections of a range of regulated air sources associated with government and private industrial facilities.

3.0 GOAL AND OBJECTIVES

The overarching goal of the DOCS one-year RPS was to achieve regulatory approval for the use of the DOCS technology to verify compliance with permitted visible opacity limits of stationary air sources. The field demonstration sites selected to support the DOCS one-year RPS included regulated stationary air sources located at Fort Wainwright, Alaska, Hill Air Force Base, Utah, Fort Hood, Texas, and a number of public and private commercial facilities within the state of Utah. The specific objectives of the DOCS technology demonstration are summarized by the following bullets:

- Establish a DOCS technical and regulatory advisory panel (TRAP) consisting of DoD air quality managers, EPA scientists and engineers, federal and state regulatory compliance personnel and academicians. The scope of the panel's activities included providing technical oversight, regulatory guidance and scientific review of the field demonstration workplan, its implementation, and implementation of results.

- Furnish the DOCS technology demonstration site personnel with the appropriate number of DOCS-validated digital cameras and ancillary equipment to support the DOCS one-year RPS.

- Provide sufficient DOCS technology training to all field demonstration site personnel and ensure that an appropriate number of Method-9-certified human observers were available to support the RPS field activities.

- Collect and compile all opacity field data recorded by the DOCS technology as well as those readings taken by Method-9-certified human observers under regulatory enforcement conditions.

- Using standard statistical significance testing, evaluate the performance of the DOCS technology relative to Method-9-certified human observers under regulatory enforcement conditions.

- Validate the performance and compatibility of new commercially available digital cameras with the DOCS technology software.

- Based on the DOCS field demonstration results, develop a draft camera-based visible opacity measurement method for review and consideration by the EPA.

4.0 MATERIALS AND METHODS

The DOCS one-year RPS field demonstration consisted of two phases conducted concurrently. During Phase I, DOCS technology was employed to determine the visible opacity of regulated stationary air sources during Method 9 compliance verification activities at Fort Wainwright, Alaska; Fort Hood, Texas; Hill Air Force Base, Utah; and at a number of public and private commercial facilities within the state of Utah.

During Phase I DOCS technology field testing, Method-9-certified observers determined the visible opacity associated with specific regulated sources once every 15 seconds for a six-minute period. The 24 visible opacity measurements were then averaged and reported as the Method 9 opacity level for the specific air source. While Method 9 field measurements were being conducted, digital photographs of the visible emissions were taken at the frequency of one photograph every 20 seconds for six minutes. At the end of the six-minute measurement period, the 18 digital photographs were then evaluated using the DOCS analysis software by personnel from the participating organizations and the results averaged to generate a DOCS technology opacity measurement.

It should be noted that the inability of the DOCS technology to measure visible opacity at a frequency equivalent to the Method-9-certified readers was due to the limitations in data processing speed associated with the Kodak DC290 digital camera. This limitation was eliminated by the newer digital camera models evaluated during Phase II of the current study.

At US military installations, DoD air quality compliance inspectors were responsible for collecting both the Method 9 and DOCS technology opacity measurements. Similarly, at the public and private commercial facilities within the state of Utah, inspectors from the Utah Division of Air Quality (UDAQ) were responsible for determining visible opacity levels using both the DOCS technology and Method 9. All Phase I field demonstration data collected over the 12-month study (including opacity determinations and digital photographs) were furnished to a DOCS quality assurance team, which had the responsibility of compiling the opacity data for statistical analysis.

During Phase II of the DOCS RPS, technology field testing focused on validating several commercially available models of digital cameras for their performance and compatibility with the DOCS technology software. Phase II was conducted by Hill Air Force air quality inspection personnel in collaboration with an EPA-approved Method 9 smoke school contractor in Syracuse, New York. In addition, the performance of the Sony, Fuji and Nikon camera models was assessed in Anchorage using an EPA-certified Method 9 smoke generator. Digital photographs of black-and-white smoke plumes of known opacity were taken using both Kodak DC290 (DC290) and commercially available Kodak Model 6490 cameras. A four-member DOCS evaluation team determined visible opacity from photographs taken by both cameras. All digital photographs were compiled on compact discs and evaluated independently by each member of the DOCS evaluation team. The average opacity determined for each photograph was then compared to the reading from the EPA-certified transmissometer to determine an average opacity difference.

4.1 *DOCS Regulatory and Technical Advisory Panel*

Prior to collection of any field data, a DOCS regulatory and technical advisory panel consisting of experienced EPA scientists and engineers, federal and state air quality regulatory personnel as well as a number of DoD engineers, scientists and compliance personnel was constituted to review the scope of the DOCS one-year RPS field demonstration. The role of the advisory panel was to provide regulatory and technical review and comment on the DOCS TFD protocol, statistical analysis methods, demonstration study conclusions and recommendations. A complete list of the DOCS RTAP members is provided in Table 2.

4.2 *Quality Assurance and Quality Control*

Since the ultimate goal of the DOCS one-year RPS demonstration was to achieve regulatory approval for the use of the DOCS technology to verify compliance with permitted visible opacity levels of stationary sources, the EMC as well as a number of opacity measurement experts from EPA regional offices including EPA Regions VI (Texas) and VIII (Colorado) were included as partners in the current study. In addition to federal environmental scientists, engineers and enforcement personnel who participated in the planning and implementation of the DOCS TFD activities, air quality regulators from the states of California, Texas and Utah provided valuable technical and regulatory oversight of the DOCS data collection activities and analysis.

Following completion of the Phase I field demonstration data collection activities, the measured opacity of each stationary source as analyzed both by the DOCS technology and by Method-9-certified human observers was furnished to the DOCS quality assurance officer by the participating organizations on a

monthly basis and stored in a Microsoft ACCESS™ database. The Hill AFB air quality office served as the central repository for all DOCS technology and Method 9 field data collection, compilation and quality assurance information. At the request of EMC, monthly conference calls were scheduled for the DOCS regulatory and technical advisory panel to review and discuss results as well as to modify field data collection procedures, when necessary. All DOCS technology training as well as DOCS cameras and ancillary equipment were furnished to participating organizations by the Hill AFB air quality manager.

During Phase II, we evaluated performance and compatibility with the DOCS statistical software of commercially available digital cameras. The DOCS field data collection consisted of taking digital photographs of smoke plumes generated as part of an EPA-approved Method 9 certification program in Syracuse, New York, using the Kodak model DC290 and DX6490 digital cameras. The opacity field results generated from use of each of these cameras were compared to the actual opacity level reported by the EPA-certified in-stack transmissometer.

In addition to collecting visible opacity data using these two digital cameras, the study evaluated compatibility with the DOCS statistical software of several additional cameras—1) Sony Cybershot DSC-WI, 2) Fuji Finepix E500 and 3) Nikon Coolpix 5200. Each was used to capture digital photographs of smoke plumes generated by a Method 9 smoke generator in Anchorage. Because the in-stack transmissometer was not functioning within the EPA's prescribed tolerance limits at the time of the digital camera field validation tests, the performance of the new digital cameras was evaluated by comparing their visible opacity measurements with those obtained using digital images taken by the DC290. The DC290 was field validated during a number of field demonstration studies including the recently attended EPA-approved smoke school held in Syracuse, N.Y.[4,5,6] Finally, it should be noted that all DOCS Phase II field data were collected under valid Method 9 conditions and included documentation of the following field data: 1) observer's distance from the source, 2) sun angle and 3) climatic conditions (*e.g*., temperature, wind speed and direction, sky conditions, precipitation, relative humidity and barometric pressure).

Following completion of the Phase II field data collection activities, a four-member DOCS opacity measurement team consisting of federal government civilian and contract personnel used the DOCS technology computer software to determine the opacity of each smoke plume captured as a digital image. Each member of the DOCS opacity measurement team was provided a compact disc containing all of the digital photographs as well as the DOCS computer software and user guide. Team members were required to work independently to determine the visible opacity of each digital photograph using the furnished computer software. Once team members had completed their analyses, the opacity results were transferred and stored electronically by the project's quality assurance officer in a relational database for subsequent statistical evaluation.

4.3 *Digital Camera Systems*

During the ESTCP-sponsored DOCS TFD, digital cameras employed to photograph visible opacity included Kodak models DC265 and DC290, both of which were validated by the DOCS technology developer prior to any field data collection. Because of their successful field deployment, these digital camera models were utilized during Phase I of the current DOCS one-year RPS.

Although there were enough Kodak modelDC265 and DC290 cameras on hand to support Phase I of the DOCS one-year RPS, these camera models are no longer commercially available. Accordingly, Phase II of the field demonstration study included an evaluation of the performance of newer digital cameras. Based on price and performance capability including enhanced picture resolution, digital data transfer capabilities, and 10X or greater optical zoom functionality, the Kodak model DX6490 was evaluated for its compatibility with the DOCS technology software at an EPA-approved Method 9 smoke school held in

Syracuse, N.Y. Several other camera models—Sony Cybershot DSC-WI, Fuji Finepix E500 and the Nikon Coolpix 5200—underwent a preliminary performance evaluation using a Method 9 smoke generator in Anchorage, Alaska.

4.4 *Statistical Test Methods—Phase I and II*

To establish credible and scientifically defensible arguments that support approval of a new visible opacity test method, data from the DOCS one-year RPS were compiled and analyzed using standard and universally acceptable statistical procedures. During the Phase I data collection activities, visible opacity measurements reported by the DOCS technology were compared against measurement by Method-9-certified visible observers or an EPA-certified transmissometer. Similarly, in Phase II, opacity results collected with the new digital camera models were compared either to an EPA-certified in-stack transmissometer or to a previously field validated digital camera system.

Designing the data collection activities to result in paired (or dependent) visible opacity measurements minimized the impact of factors that might contribute to an observed difference in performance between opacity measurement approaches (*e.g.*, weather conditions). The following sections provide a brief description of the statistical test methods employed in drawing scientifically defensible conclusions from the field demonstration results.

4.4.1 Significance Testing

In the design of the Phase I field tests, visible opacity associated with regulated stationary air sources was measured by Method-9-certified human observers and the DOCS technology simultaneously. A standard statistical procedure—significance testing—was employed to evaluate the equivalency of the two measurement methods. .

In significance testing, a null hypothesis (H_o) is developed that will be assumed to be true in the absence of strong quantitative evidence to the contrary. The strength of the data may be evaluated statistically using either a paired sample *t*-test or by constructing a confidence interval about the mean difference between the two methods. The results of the paired sample *t*-test and/or the range of the confidence interval will provide the basis for either rejecting or not rejecting H_o.

H_o for the present study may be stated as follows: "*the true mean difference between Method 9 readings and those reported by the DOCS technology is zero.*" This statement reflects the decision-maker's conclusion that the two opacity measurement methods are equivalent. Similarly, the alternative hypothesis (H_a) may be constructed as follows: "*the true mean difference between Method 9 readings and those reported by the DOCS technology is* not *zero.*" If the strength of the data is sufficient to reject the null hypothesis, the decision-maker will conclude that H_a is true. In statistical terms, these hypotheses can be presented as follows:

Null Hypothesis (H_o): $\delta_o = 0$

Alternative Hypothesis (H_o): $\delta_o \neq 0$

Where:

δ_o = the true mean difference between opacity readings made by Method 9 and the DOCS technology

---

Since the true *mean difference* between the two visible opacity measurement methods (δ_o) can never be known exactly, it must be determined by calculating the average difference. Equation 1.1 was used to calculate the average of the paired opacity differences from the sampling data.

$$\bar{d} = \frac{\sum_{i=1}^{i=n} d_i}{n} = \frac{1}{n} \bullet \sum_{i=1}^{i=n} \left(y_{1,i} - y_{2,i} \right) \tag{1.1}$$

Where:

$\bar{d}$ = average difference between paired opacity measurements

$y_{1,i}$, $y_{2,i}$ = opacity measurement "*i*" recorded by the Method 9 observers and the DOCS, respectively

n = number of paired opacity measurements

Equations 1.2 and 1.3 were used to determine the sample variance and standard error of the average differences between opacity readings, respectively. To employ the *paired t-test* to draw defensible conclusions from the data set requires that the decision-maker select a level of significance (α) from which a critical *t*-value may be determined.

$$\text{Variance: } s_d^{\,2} = \frac{\sum_{i=1}^{i=n} \left(d_i - \bar{d} \right)^2}{n-1} \tag{1.2}$$

$$\text{Standard Error: } s_{\bar{d}} = \frac{s_d}{\sqrt{n}} \tag{1.3}$$

Where:

d_i = difference between paired opacity measurements

Given an assigned level of significance, α, and degrees of freedom (n-1), the critical *t*-values and test statistic (t_{test}) are defined by the following expressions, which are compared to determine if the strength of the field data is sufficient to reject the null hypothesis, H_o.

$$\text{Critical } t\text{-values}: t_{\frac{\alpha}{2}, n-1} \text{ and } -t_{\frac{\alpha}{2}, n-1}$$

$$\text{Test statistic}: t_{\text{test}} = \frac{\bar{d} - \delta_o}{\frac{s_d}{\sqrt{n}}}$$

Where:

δ_0 = true mean difference (assumed to be zero)

Test Condition:

Test Condition : If $t_{\text{test}} > t_{\frac{\alpha}{2}, n-1}$ or $t_{\text{test}} < -t_{\frac{\alpha}{2}, n-1}$, then the null hypothesis, H_o, is **rejected**.

Test Condition : If $t_{\text{test}} > t_{\frac{\alpha}{2}, n-1}$ or $t_{\text{test}} < -t_{\frac{\alpha}{2}, n-1}$, then the null hypothesis, H_o, is **rejected**.

A method statistically equivalent to the paired *t*-test for determining whether the strength of the data is sufficient to reject the null hypothesis involves generating a (1-α) confidence interval about the average difference using Equation 1.4[10,11]. If the confidence interval contains zero, the conclusion will be that, at the stated confidence level (1-α), the true mean difference between the two opacity measurement methods (δ_o) is insignificant and, therefore, the strength of the data is insufficient to reject the null hypothesis H_o (*i.e.*, the two opacity measurement methods are statistically equivalent).

Conversely, if the confidence interval does not contain zero, the conclusion will be that, at the stated confidence level (1-α), the true mean difference between the opacity readings of the two measurement methods (δ_o) is significant and therefore, the evidence is sufficient to reject the null hypothesis, H_o, and the decision-maker will accept the alternative hypothesis, H_a (*i.e.*, the two opacity measurement methods are statistically different), as true.

$$\bar{d} \pm t_{\frac{\alpha}{2}, n-1} \bullet s_{\bar{d}} \qquad (1.4)$$

Where:

$t_{\frac{\alpha}{2}, n-1}$ = critical *t*-values (from *t*-distribution tables)

$\frac{\alpha}{2}$ = tail area probability

α = level of significance (*i.e.*, for 99% confidence, $\alpha = 0.01$)

$n-1$ = degrees of freedom

s_d = standard error of the differences in opacity readings

5.0 RESULTS

5.1 *Phase I*

During Phase I of the DOCS one-year RPS, the state of Utah Division of Air Quality, in conjunction with Fort Wainwright, Hill AFB and Fort Hood, completed opacity measurements of 241 regulated air processes using both Method-9-certified smoke readers and the DOCS technology. The range of regulated air processes evaluated by the two methods included 1) industrial process scrubbers, 2) coal-fired boilers, 3) industrial air strippers, 4) industrial bag houses, 5) emergency power generators, 6) asphalt paving operations, 7) oil refining, 8) chlorine manufacturing, 9) steel production, 10) meat packing operations, 11) incineration, 12) gypsum manufacturing, 13) gas/oil distribution systems and 14) metal coating facilities. A complete list of the types of air sources whose emissions were evaluated during Phase I of the DOCS one-year RPS is provided in Appendix A.

At the recommendation of the DOCS RTAP, decisions resulting from these field tests were to be supported at the 99% confidence level. Therefore, a significance level (α) of 0.01 was employed throughout the analysis. Table 3 provides a summary of the statistical analysis of the DOCS one-year RPS field demonstration. It should be noted that, in determining the average difference in opacity measurements between the two methods, the DOCS opacity value was subtracted *from* the Method 9 opacity observation. Finally, for the majority of regulated air sources evaluated in Phase I of the DOCS field demonstration study, a visible opacity level of zero was reported by the Method 9-certified human observers. However, because of the importance of statistically comparing the performance of the DOCS technology relative to Method-9-certified human observers for regulated stationary air sources whose emissions are clearly characterized by a nonzero opacity level, Table 3 provides a statistical assessment of the two measurement approaches using all collected field data (241 regulated air sources) as well as only those regulated air sources that reported nonzero visible opacity levels (36 regulated air sources).

The average difference in opacity readings between the two methods was *-1.12%* when all the regulated stationary source opacity data were taken into account. Because the DOCS opacity measurement was subtracted from the Method 9-certified human observer opacity reading, this finding suggests that the DOCS technology reports slightly higher opacity levels than the Method-9-certified human observers. When the data set was limited to only those regulated stationary sources for which a nonzero opacity level was recorded by the Method 9-certified human observers, the average difference in opacity readings between the two methods was found to be *+1.20%*, a finding that indicates that Method-9-certified human observers reported opacity values that were slightly greater than those measured by the DOCS technology.

In applying statistical significance testing, the results summarized in Table 3 suggest that, when the opacity data from all 241 regulated air sources are taken into account, comparison of the critical *t*-value with the test statistic supports the rejection of the null hypothesis. This finding is tantamount to concluding that the two opacity approaches are different and that, on average, the DOCS technology measures visible opacity at a level that is approximately *1.12% greater* than the visible opacity measured by Method-9-certified human observers.

In contrast, when only those regulated stationary air sources for which a nonzero visible opacity was detected by the Method-9-certified human observers are used in the statistical analysis, comparison of the critical *t*-value with the test statistic does not support rejection of the null hypothesis. This result indicates that, when measuring nonzero opacity levels, the accuracy of the two measurement approaches *is statistically equivalent.*

Table 3 Statistical Significance Testing of DOCS Field Demonstration Data

Data Type	***n***[1]	**Average Difference**[2] **(%)**	**Test Statistic**[3]	**Critical *t*-value**[4]	**Rejection of Null Hypothesis**
All data	241	-1.12	-41.8	2.576	yes
All observations where visual opacity was reported to be greater than zero by Method-9-certified human observers	36	1.20	0.67	2.704	no

[1]number of regulated air sources evaluated
[2]average difference is computed based on the following equation: Opacity level (Method 9) – Opacity level (DOCS)
[3]computed based on field data
[4]taken from standard *t*-tables assuming a 99% confidence level ($\alpha = 0.01$)

Similar statistically supportable conclusions can be drawn by evaluating the 99% confidence interval about the average difference in opacity readings. Table 4 summarizes the results of this statistical approach. When data from all 241 regulated stationary air sources are taken into account, the 99% confidence interval about the average opacity difference extends over a range that does not include the value of zero. In practical terms, this finding supports the conclusion that the two methods are statistically different and that the DOCS technology measures visible opacity at levels that are, on average, 1.12% *higher* than those reported by Method-9-certified human observers.

Table 4 Evaluation of the 99% Confidence Interval about the Average Opacity Difference

Data Type	***n***[1]	**Average Difference**[2] **(%)**	**99 % Confidence Interval**
All data	241	-1.12	-1.18 < -1.12 < -1.06
All observations where visual opacity was reported to be greater than zero by Method 9-certified human observers	36	1.20	-1.77 < 1.20 < 4.16

[1]number of regulated air sources evaluated
[2]average difference is computed based on the following equation: Opacity level (Method 9) – Opacity level (DOCS)

Conversely, when only those regulated stationary air sources for which a nonzero visible opacity was measured by the Method-9-certified human observers are included in the statistical analysis, the 99% confidence about the average difference extends over a range that does include the value of zero. The

conclusion drawn from this finding is that the two opacity measurement methods are statistically equivalent or alternatively, there is less than a 1% probability that the two methods are different[10,11].

5.1.1 Practical Considerations

An important practical consideration in determining visible opacity using any validated approach including the DOCS technology is the impact of weather conditions on measurement accuracy. As color contrast between the plume and background diminishes, apparent plume opacity decreases, which can lead to an underestimation (or negative bias) of opacity results[2]. During at least some of the visible opacity measurements completed by Utah Division of Air Quality regulatory inspectors, this phenomenon occurred. When sky is employed as the background against which plume opacity is determined, visible opacity measurement using any approach (including the DOCS technology) is not recommended under dark or heavily overcast and cloudy conditions. Failure to recognize the effect of weather conditions on visible opacity measurement can result in significant underestimation of the true plume opacity. Finally, the variability in DOCS accuracy as a function of weather conditions illustrated the importance of providing to DOCS technology users appropriate technical guidance together with periodic refresher training.

5.2 *Phase II*

During Phase II of the DOCS one-year RPS, compatibility of new commercially available cameras with the DOCS analysis software was field tested. Based on functionality and cost, four digital cameras were evaluated: 1) Kodak DX6490, 2) Sony Cybershot DSC-WI, 3) Fuji Finepix E500 and the 4) Nikon Coolpix 5200. Performance of Kodak model DX6490 was evaluated at an EPA-approved Method 9 smoke school held in Syracuse, N.Y. Its results were compared to visible opacity measurements made by an EPA-certified in-stack transmissometer The Sony, Fuji and Nikon cameras were assessed in Anchorage by using an EPA-certified Method 9 smoke generator to compare their results to those of the DC290, whose performance was earlier[4,5,6] validated.

5.2.1 Kodak DX6490

The Kodak DX6490 was evaluated during an EPA-approved Method 9 smoke school conducted in Syracuse, N.Y. in December 2004. During digital camera field validation tests, smoke plumes of known opacity were evaluated using photographs taken by the DC290 as well as the Kodak DX6490 digital camera. Average DOCS opacity determinations recorded by a four-member DOCS technical team using photographs from each camera, were then compared to the “true” opacity as measured by the EPA-certified in-line transmissometer.

To determine whether a particular digital camera/DOCS analysis software combination measures visible opacity as accurately as the EPA-certified in-line transmissometer, an average difference in recorded opacity measurements was determined between each digital camera/DOCS analysis software combination and the transmissometer, as well as the 99% confidence interval about the average opacity difference. By applying a standard statistical significance testing approach and finding that the 99% confidence interval includes the value of zero, the conclusion one may draw from the data set is that there is no significant difference between the two opacity measurement methods and that the accuracy of the methods is statistically equivalent. Conversely, if the 99% confidence interval does not include the value of zero, the conclusion drawn from the field data will be that there is a significant difference in the two opacity measurement methods and that the methods produce statistically different opacity readings. The results from these field tests are summarized in Table 5.

Table 5 Performance of Kodak DC290 and Kodak DX6490 Cameras at Method 9 Smoke School[1]

Camera Model	Opacity Range[2]	No. of Smoke Plume Photographs (*n*)	Average Difference % (Camera – Transmissometer)	99% Confidence Limit	Significant Difference?
DC290	0–40%	55	-1.36	-4.91<-1.36<2.19	No
DC290	0–100%	100	-0.72	-4.24<-0.72<2.79	No
DX6490	0–40%	55	-7.87	-17.77<-7.87<2.04	No
DX6490	0–100%	100	-7.30	-12.74<-7.30<-1.85	Yes

[1]Syracuse, N.Y., Method 9 Smoke School
[2]Established by EPA-Certified Transmissometer

Digital camera validation results from the Syracuse, N.Y., Method 9 smoke school indicate that over the full range of opacity (0–100%) as well as for the opacity range of regulatory concern (0–40%), the DC290/DOCS analysis software combination yielded opacity values that are not statistically different from those recorded by the EPA-certified transmissometer. The 99% confidence interval for both ranges of opacity investigated includea the value of zero. Therefore, although the data suggest that the DC290/DOCS analysis software combination determines visible opacity at levels that are, on average, 5.67% *lower* than the EPA-certified transmissometer over the full range of opacity, this difference was found to be statistically insignificant. The conclusion drawn from these data is that the DC290/DOCS analysis software combination determines visible opacity with accuracy that is statistically equivalent to that of the EPA-certified transmissometer over the full range of opacity.

Similarly, the Kodak DX6490 digital camera/DOCS statistical software combination was found to yield visible opacity measurements that are, on average, 7.30% *lower* than the EPA-certified transmissometer over the full range of opacity (0–100%). However, over the same opacity range, the 99% confidence interval about the average opacity difference did not include the value of zero, indicating that the differences in opacity measurements recorded by the two methods are statistically significant. In other words, the Kodak DX6490 digital camera/DOCS analysis software combination was found not to be statistically equivalent to the EPA-certified transmissometer over the full range of opacity (0–100%).

In contrast, when the opacity range was limited to 0–40% opacity, the 99% confidence interval about the average opacity difference did include the value of zero. This observation indicates that, although the Kodak DX6490 digital camera/DOCS analysis software combination measures visible opacity at levels that are, on average, 7.87% *lower* than the EPA certified transmissometer over the 0–40% opacity range, this difference was found to be statistically insignificant. The conclusion drawn from these results is that, when the visible opacity is limited to 40% or less, the Kodak DX6490 digital camera/DOCS analysis software combination determines visible opacity with an accuracy that is statistically equivalent to that of the EPA-certified transmissometer.

5.2.2 Sony Cybershot DSC-WI, Fuji Finepix E500 and Nikon Coolpix 5200

During field validation testing of Sony Cybershot DSC-WI, Fuji Finepix E500 and Nikon Coolpix 5200 cameras in Anchorage, a Method 9 smoke generator was used to generate black and white smoke plumes

of varying opacity. However, because the response of the in-stack transmissometer during calibration testing was outside the permissible tolerance established by EPA standard protocol, digital photographs of visible opacity taken by the DC290 and analyzed by the DOCS technology were used as the accuracy benchmarks. The decision to use the DC290-based opacity measurements to evaluate the new digital camera systems was supported by its performance[4,5] at various EPA-approved Method 9 smoke schools. At the Syracuse, N.Y., Method 9 smoke school, opacity readings recorded by the DOCS system using photographs taken with the DC290 were found to be statistically equivalent to opacity measurements reported by the EPA-certified in-stack transmissometer over the entire range of opacity evaluated.

By applying the results of the DC290 as the "true" opacity, visible opacity measurements recorded by the Sony Cybershot DSC-WI, Fuji Finepix E500 and Nikon Coolpix 5200 could be evaluated. To evaluate whether performance of any of the new digital cameras was statistically different at the 0.01 significance level from that of the DC290, the average difference in opacity readings and the 99% confidence level about the average were computed. Table 6 summarizes the statistical evaluation of the digital camera validation results.

Examination of the data summarized in Table 6 reveals that the digital camera validation tests yielded mixed results. Over the full range of opacity evaluated (0–100%), average opacity differences recorded between the DC290 and the Sony Cybershot DSC-WI, Fuji Finepix E500 and Nikon Coolpix 5200 camera models were 2.42%, -1.13% and 1.85%, respectively. At the 0.01 significance level, none of the new digital cameras was found to yield visible opacity results that were statistically equivalent to the DC290. This finding is supported by the observation that, for each of the new digital cameras tested, the 99% confidence limits associated with the average opacity difference excluded the value of zero.

Table 6 Field Validation: Sony Cybershot DSC-WI, Fuji Finepix E500 and Nikon Coolpix 5200[1]

Camera Model	Opacity Range[2] %	Number of Smoke Plume Photographs (n)	Average Difference % (Kodak DC290 – New Digital Camera)	99% Confidence Interval	Significant Difference?
Sony Cybershot DSC-WI	0–100	810	2.42	1.16 <2.42< 3.68	Yes
Sony Cybershot DSC-WI	0–40	679	0.11	-0.81 <0.11< 1.04	No
Fuji Finepix E500	0–100	810	-1.13	-2.2 <-1.13<-0.05	Yes
Fuji Finepix E500	0–40	679	-2.20	-2.98 <-2.20<-1.42	Yes
Nikon Coolpix 5200	0–100	810	1.85	0.65 <1.85<3.05	Yes
Nikon Coolpix 5200	0–40	679	-0.46	-1.24 <-0.46<0.32	No

[1] Performance of the Sony, Fuji and Nikon cameras was evaluated in Anchorage
[2] Opacity range was established by Kodak DC290 camera opacity readings

However, limiting the statistical analysis to the opacity range of regulatory interest, *i.e.*, 0–40%, considerably alters the conclusions regarding digital camera performance. Over the opacity range 0–40%, the average opacity differences recorded between the DC290 and the Sony Cybershot DSC-WI, Fuji Finepix E500 and Nikon Coolpix 5200 camera models were 0.11%, -2.20% and -0.46%, respectively.

Moreover, at the 0.01 significance level, both the Sony Cybershot DSC-WI and the Nikon Coolpix 5200 were found to yield visible opacity results statistically equivalent to those reported by the DC290. In other words, the 99% confidence interval associated with the average opacity difference recorded by these two digital cameras includes the value of zero. Statistically, this finding supports the conclusion that the performance of these two new digital cameras was equivalent to that of the previously validated DC290. In contrast, the Fuji Finepix E500, recorded visible opacity results that were found to be statistically different from the those recorded by the DC290 over the 0–40% opacity range.

6.0 DISCUSSION

Although previous ESTCP-funded field tests demonstrated the DOCS technology to be an accurate, reliable digital-camera-based method for measuring visible opacity associated with stationary air sources, these activities were conducted under relatively controlled conditions. Most of the earlier field data collection was conducted at either an EPA-approved Method 9 smoke school or at DoD industrial or commercial sites at which plume opacity was controlled by facility personnel.

Recognizing the importance of documenting the performance of the DOCS technology under actual compliance enforcement conditions, EMC, in collaboration with several EPA regions and state air regulatory agencies, requested implementation of a DOCS one-year RPS. Data collected during this effort would be used in conjunction with performance data collected in earlier DOCS technology field demonstrations to support the development and promulgation of a new EPA-approved visible opacity measurement method[13].

This DOCS technology one-year RPS field demonstration was conducted in two phases. Phase I focused on comparing performance of the DOCS technology to Method-9-certiifed human observers in measuring the visible opacity of stationary air sources under regulatory enforcement conditions. A total of 241 regulated air sources from Fort Hood, Hill AFB, Fort Wainwright, and a number of government and private industrial sources within the state of Utah were evaluated during Phase I of the current DOCS TFD.

The average opacity difference found between the DOCS technology and Method 9-certified human observers was 1.12%. Although this difference is relatively small, statistical analysis of the field data confirmed that the opacity difference was significant. In other words, on average, the DOCS technology would be expected to measure visible opacity at a value 1.12% greater than the Method 9-certified human observer's.

Of the 241 regulated air sources evaluated, most (205) were reported (by Method-9-certified human observers) to have no discernable opacity in their emissions. Because of the importance of characterizing differences in opacity measurements between Method-9-certified human observers and the DOCS technology for visible air emissions, the DOCS RTAP recommended that a separate statistical comparison be made of those air sources with reported nonzero visible opacity.

Analysis of 36 regulated air sources for which nonzero visible opacity levels were reported by the Method 9-certified human observers found the average opacity difference between the DOCS technology and the

Method-9-certified human observers was 1.20%. Moreover, based on results from statistical significance testing, this difference was found to be not significant. In other words, the small difference found in the average opacity measurements between the DOCS technology and the Method-9-certified human observers could be attributed to random variability (or error) and the two measurement approaches were statistically equivalent.

Phase II of the DOCS one-year RPS was designed to evaluate performance and compatibility with the DOCS technology software of a series of new digital cameras. The impetus for conducting Phase II was the fact that digital cameras employed during the earlier DOCS field demonstration activities (including Phase I of the current field demonstration—Kodak models DC265 and DC290—are no longer commercially available. To ensure that future DOCS technology users have access to affordable digital cameras that have been field validated with the DOCS technology software, the following models of digital cameras were evaluated as part of the current Phase II DOCS technology study: 1) Kodak model DX6490, 2) Sony Cybershot DSC-WI, 3) Fuji Finepix E500 and 4) Nikon Coolpix 5200.

Kodak model DX6490, which was evaluated during an EPA-approved Method 9 smoke school held in Syracuse, N.Y., was found to measure visible opacity with accuracy equivalent to the EPA-certified transmissometer in the visible opacity range 0–40%. Above 40% opacity, Kodak model DX6490 measured visible opacity, on average, 7.3%, lower than the EPA-certified transmissometer.

Sony Cybershot DSC-WI, Fuji Finepix E500 and Nikon Coolpix 5200 digital cameras were evaluated by taking digital photographs of a series of black and white smoke plumes generated by a Method 9 smoke generator in Anchorage. Unfortunately, because the in-stack transmissometer response during instrument calibration was outside the tolerance limits established by EPA protocol, accuracy of these digital cameras was established by comparing their results with opacity measurements achieved through the use of the Kodak model DC290 digital camera. Adopting DC290 opacity measurements as the performance benchmark was supported by its extensive field testing and validation at EPA-approved Method 9 smoke schools including one recently held in Syracuse, N.Y.

Results from the Anchorage digital camera validation tests indicate that, over the full range of opacity (*i.e.*, 0–100%), none of the digital cameras was statistically equivalent in performance to the DC290. Although the difference in measurement response of the new digital cameras to the DC290 was less than 3.0%, statistically the differences were found to be significant.

In the limited opacity range 0–40% opacity differences reported by both the Sony Cybershot DSC-WI and the Nikon Coolpix 5200 were found to be not statistically significant. That is, in the opacity range 0–40%, accuracy of the Sony Cybershot DSC-WI and Nikon Coolpix 5200 in measuring visible opacity was equivalent to the DC290's. In contrast, the Fuji Finepix E500 was found to measure visible opacity values that were, on average, 2.2% less than the DC290 in the opacity range 0–40%.

The practical conclusion drawn from the Phase II field demonstration activities is that, for visible opacity values of 0–40%, one may use Kodak model DX6490, Sony Cybershot DSC-WI and Nikon Coolpix 5200 cameras with the DOCS technology software to determine visible opacity, and have reasonable assurance that the accuracy of the results will be equal to or better than those achievable by the use of the DC290. On the other hand, the Fuji Finepix E500 digital camera was found to measure visible opacity at values statistically different from the DC290's over the entire visible opacity range investigated.

Given the successful field demonstration of the DOCS technology under regulatory enforcement conditions, and the identification and field validation of commercially available digital camera systems that can support the DOCS technology, EMC in conjunction with DoD has developed a new digital camera-based visible opacity measurement method[13] that, under certain circumstances, may be employed

in lieu of Method 9. The draft camera-based visible opacity measurement method, which is currently undergoing public comment, is presented in Appendix B.

7.0 CONCLUSIONS

The DOCS one-year RPS was formulated to answer critical questions regarding performance of the digital-camera-based opacity measurement system under regulatory enforcement conditions. Based on statistical analysis of the technology demonstration data set, the following conclusions can be drawn:

- Over the range of visible opacity of regulatory interest (*i.e*., 0–40%), accuracy of the DOCS technology is statistically equivalent to Method 9.

- Over the full range of visible opacity (*i.e*., 0–100%), DOCS technology measures visible opacity with accuracy that is, on average, 1.12% greater than Method 9-certified human observers.

- Over the range of visible opacity of regulatory interest (*i.e*., 0–40%), accuracy of Kodak DX6490, Sony Cybershot DSC-WI and Nikon Coolpix 5200 cameras in measuring visible opacity was found to be statistically equivalent to that of the field-validated Kodak DC290.

- Based on the successful field demonstration of the DOCS technology, a draft camera-based visible opacity measurement method has been developed and submitted to the EPA for technical and regulatory review[13].

8.0 REFERENCES

1. Reitze, A. W. (2001**)** *Air Pollution Control Law: Compliance and Enforcement* Environmental Law Institute, Washington, D.C.

2. *Federal Register* (1971**) "**Method 9—Visual Determination of the Opacity of Emissions from Stationary Sources" vol. 36 No. 247 December 23.

3. Environmental Security Technology Certification Program (2005) "An Alternative to EPA Method 9—Field Validation of the Digital Opacity Compliance System (DOCS)" Draft Final Report Project No. CP-200119 February 2005

4. McFarland, M.J., Stone, D.A., Calidonna, M. J., Rasmussen, S. L., and S. H. Terry (2003) "Evaluation of the Digital Opacity Compliance System (DOCS) in High Mountain Desert Environment" *Journal of the Air & Waste Management Association* vol. 53 pp 724–730.

5. McFarland, M. J., Stone, D.A., Calidonna, M.J., Kerch, P.E., Rasmussen, S. L. and S.H. Terry, (2004) "Measuring Visual Opacity Using Digital Imaging Technology" *Journal of the Air & Waste Management Association* vol. 54 pp. 296–306.

6. McFarland, M. J., Stone, D.A., Rasmussen, S. L., Calidonna, M.J., Kerch, P.E., and J. A. Gunter (2004) "Evaluation of the Digital Opacity Compliance System (DOCS) at Military and Commercial Industrial Sites" *Federal Facilities Environmental Journal* vol. 15, Issue 2 pp. 73–81.

7. *Federal Register* (1997) AD-FRL-5725-2 "National Ambient Air Quality Standards for Particulate Matter—Final Rule" 40 CFR Part 50, July 18.

8. Environmental Security Technology Certification Program (2005) "An Alternative to EPA Method 9—Field Validation of the Digital Opacity Compliance System (DOCS)" Draft Cost and Performance Report: Project No. CP-200119 February 2005

9. Stretch, J. and B. Pfaff (1999) *Summary Report for the Joint NASA Space Dynamics Laboratory Remote Sensing Project on an Optical Digital Environmental Compliance System (ODECS)* Scientech Inc.

10. Moore, D.S. McCabe, G.P. (1993) *Introduction to the Practice of Statistics*. W.H. Freeman: New York.

11. Gilbert, R.O (1987). *Statistical Methods for Environmental Pollution Monitoring*: Wiley & Sons: New York.

12. EMTIC EM-009, "Method 9—Visual Determination of the Opacity of Emissions from Stationary Sources", Emissions Measurement Branch, Technical Support Division, OAQPS, EPA, October 25, 1990.

13. U.S. Environmental Protection Agency–Emissions Measurement Center (2005): "Determination of Visible Emission Opacity from Stationary Sources Using Computer-Based Photographic Analysis Systems" URL: http://www.epa.gov/ttn/emc/prelim/pre-008.pdf

APPENDIX A

Types of Air Sources Evaluated During DOCS One-Year Regulatory Pilot Study (RPS)

EQUIPMENT	CONTROL	EMISSION POINT
Abrasive cleaning	Baghouse	horizontal stack
Abrasive cleaning	Control internal to blaster	vertical stack
Abrasive cleaning	Baghouse	vertical stack
Abrasive cleaning	Cyclone and baghouse	vertical stack
Anodizing	Scrubber	vertical stack
Arc wire spray booth	Scrubber	vertical stack
Arc wire spray booth	None	vertical stack
Asphalt dryer	Baghouse	vertical stack
Boiler	None	vertical stack
Cadmium plating	Scrubber	vertical stack
Cadmium stripping	Scrubber	vertical stack
Chrome plating	Scrubber	vertical stack
Chrome stripping tank	Scrubber	vertical stack
Coal-fired boiler	None	vertical stack
Coal-fired boiler	Scrubber	vertical stack
Concrete batch plant	Baghouse	vertical stack
Dryers/screens/silos	Baghouse	vertical stack
Dual-fired boiler	None	vertical stack
Fuel oil boiler	None	vertical stack
General sanding and carpentry processes	Cyclone	vertical stack
Generator	Natural gas	vertical stack
Generator	Low-NOx burner technology	vertical stack
Generator	Electrostatic precipitator	vertical stack
Generator	None	vertical stack
Generator	None	horizontal stack
Grinder /kiln	Wet mist collector	vertical stack
High-velocity oxygen fuel spray	Dry filters	vertical stack
Incinerator	None	vertical stack
Incinerator	Secondary burner	vertical stack
Kiln	Scrubber	vertical stack
Lathe spray booth	None	vertical stack
Main stack	Scrubber	vertical stack
Mixed waste treatment	Baghouse	horizontal vent
Mixing tank	None	vertical stack
Natural gas compressor engines	Clean fuel	vertical stack
Natural gas engine/generator	Catalytic converter	vertical stack
Nickel plating	Scrubber	vertical stack
Oxygen flame spray booth	None	vertical stack
Paint booth	None	vertical stack
Paint booth	Particulate filter	vertical stack

Paint booth	Particulate filter	horizontal stack
Plasma arc flame spray booth	Scrubber	vertical stack
Silos and material transfer	Baghouse	vertical stack
SO_2 scrubber	Wet scrubber	vertical stack
Thermal metal spray unit	Scrubber	vertical stack
Turbine	None	vertical stack
Wastewater air stripper	Air stripper	vertical stack
Wood shop	Baghouse	vertical stack

APPENDIX B

Determination of Visible Emission Opacity from Stationary Sources Using Computer-Based Photographic Analysis Systems—Draft Method

INTRODUCTION

(a) Many stationary sources discharge visible emissions into the atmosphere, which are usually in the shape of a plume. The following method describes a technical approach for determining the visible opacity of plume emissions through the use of photographs taken of the regulated source under compliance enforcement conditions. The photographs are processed using computer software that determines visible opacity using information available from the digital or digitized images. The visible opacity determination method includes procedures for the validation of both the computer opacity analysis software system as well as performance specifications for camera hardware.

(b) The appearance of a plume as viewed by an observer depends upon a number of variables, some of which may be controllable in the field. Variables that can be controlled to an extent to which they no longer exert a significant influence upon plume appearance include: angle of the observer with respect to the plume; angle of the observer with respect to the sun; point of observation of attached and detached steam plume; and angle of the observer with respect to the plume emitted from a rectangular stack with a large length-to-width ratio. The following visible opacity determination method includes specific criteria applicable to these variables.

(c) Other variables that may not be controllable in the field are luminescence and color contrast between the plume and the background against which the plume is viewed. These variables exert an influence upon the appearance of the plume and can affect the ability of the technology to assign accurately opacity values to the observed plume. Studies of the theory of plume opacity and field studies have demonstrated that a plume is most visible and presents the greatest apparent opacity when viewed against a contrasting background[1,2]. Accordingly, the opacity of a plume viewed under conditions where a contrasting background is present can be assigned with the greatest degree of accuracy.

Under conditions presenting a less-contrasting background, the apparent opacity of a plume is less and approaches zero as the color and luminescence contrast decrease toward zero. As a result, significant negative bias and negative errors can be made when a plume is viewed under less contrasting conditions. A negative bias decreases rather than increases the possibility that a facility will be incorrectly cited for a violation of opacity standards as a result of observer error.

(d) The accuracy of any photographic computer software opacity determination system must be taken into account when determining possible violations of applicable opacity standards. Field demonstration studies have been undertaken to determine the accuracy and reliability by a prototype opacity measurement computer software system[3,4,5,6,7]. The results of these demonstration studies (field trials), which involved the computer analysis of over twenty thousand (20,000) photographs of smoke plumes, were used to establish achievable accuracy and system reliability standards.

1. PRINCIPLE AND APPLICABILITY

1.1 Principle. The opacity of emissions from stationary sources is determined by the application of a validated photographic computer software opacity analysis system to process the digital or digitized images of the regulated emissions.

1.2 Applicability. This method is applicable for the determination of the opacity of emissions from stationary sources.

2. PROCEDURES

The validated photographic computer software analysis system shall use the following procedures for determining the opacity of visible plume emissions from digital or digitized photographs of regulated stationary sources.

2.1 Position. Photographs of visible emissions that will be utilized to establish compliance certification shall be taken at a distance sufficient to provide a clear view of the plume with the sun oriented in the 140º sector to the photographer's back. Enhanced focus of the visible emissions through use of an optical and/or digital zoom feature may be employed in taking photographs of plume opacity.

Consistent with maintaining the above requirement, photographs of visible emissions for compliance certification purposes shall, to the extent possible, be taken from a position such that the camera's line of vision is approximately perpendicular to the plume direction and, when taking photographs of visible emissions from rectangular outlets (*e.g.*, roof monitors, open baghouses, noncircular stacks), approximately perpendicular to the longer axis of the outlet. The camera's line of sight should not include more than one plume at a time when multiple stacks are involved, and, in any case, the photographer shall take plume emission photographs with a line of site perpendicular to the longer axis of such a set of multiple stacks.

2.2 Field Records. All photographs of regulated visible emissions shall be accompanied by records that include 1) the name of the facility, 2) emission location, 3) facility type, 4) photographer's name and affiliation, 5) opacity computer software user's name and affiliation (if different from photographer) and 6) the date and time at which the photographs were taken. The estimated distance to the emission location, the type and magnitude of any optical feature employed (*e.g.*, optical zoom, digital zoom, etc.), approximate wind direction, estimated wind speed, description of sky conditions (*e.g.*, presence and color of clouds), and plume background shall be documented and recorded on a field data sheet at the time plume emission photographs are taken and provided to the regulatory authority as part of the compliance certification demonstration.

2.3 Observations. When utilizing a validated photographic computer software opacity analysis system, the opacity determination shall be made at the point of greatest opacity in that portion of the plume where condensed water vapor is not present.

2.3.1 Attached Steam Plumes. When condensed water vapor is present with the plume as it emerges from the emission outlet, photographs of the visible emission must capture that portion of the plume opacity beyond which condensed water vapor is no longer visible.

2.3.2 Detached Steam Plume. When water vapor in the plume condenses and becomes visible at a distinct distance from the emission outlet, the opacity of emission should be evaluated at the emission outlet point to the condensation of water vapor and the formation of the steam plume.

2.4 Recording Observations. The number of plume photographs required to certify regulatory compliance shall depend on the scope of the observation. When the purpose of the emission observation is to establish the presence or absence of visible opacity (*i*.e., field screening), field procedures described under Phase I field activities shall be followed. Alternatively, when the presence of visible opacity has been confirmed and verification that the visible opacity level is within regulatorially permitted limits is required, field procedures described under Phase II field activities shall be followed.

2.4.1 Phase I Field Observation Activities. To establish the presence or absence of visible opacity from a regulated source, the computer analysis of a **single** photograph taken under appropriate field conditions (Sections 2.1 and 2.2) shall be conducted using a regulatorially approved photographic computer software opacity analysis system. Results from Phase I opacity field activities confirming the absence of any visible emissions from a regulated source shall be certified by the responsible facility official. All Phase I visible opacity confirmation photographs as well as results generated by the computer software opacity analysis system shall be documented and retained by the regulated facility for a period of no less than five (5) years.

2.4.2 Phase II Field Observation Activities. Once the presence of visible opacity has been confirmed (either through application of Phase I observation activity procedures or by visible observation), determination of the visible opacity level shall be established by calculating the average opacity from a set of at least fifteen (15) individual photographs of the regulated source taken under compliance verification conditions. Each plume photograph used to establish the average visible opacity level of the regulated source shall be taken at time intervals of no less than thirty (30) seconds. Ensuring that the Phase II opacity determination test period spans at least 7.5 minutes reduces the risk that an emission spike will bias field measurement results.

2.4.3 Phase II Data Reduction. Opacity shall be determined as an average of fifteen (15) individual and consecutive plume opacity estimates as determined using a regulatorially valid photographic computer software opacity analysis system. Each of the fifteen (15) opacity determinations shall be recorded from plume emissions photographed once every thirty (30) seconds for 7.5 minutes. For each set of fifteen (15) opacity estimates, the average opacity of the regulated air source shall be calculated by summing the opacity of the fifteen (15) opacity estimates and dividing this sum by fifteen (15). If an applicable standard specifies an averaging time requiring more than fifteen (15) observations, the average opacity for all observations made during the specified time period shall be determined.

3. QUALIFICATION AND TESTING

3.1 Certification Requirements.

3.1.1 Software. To certify a photographic computer software opacity analysis system as a regulatorially valid visible opacity measurement method, the technology must demonstrate the ability to estimate the plume opacity of a series of standard images. Specifically, the technology shall determine the visible opacity of a set of three hundred (300) regulatorially-approved standard photographs of one hundred fifty (150) black and one hundred fifty (150) white plumes generated from EPA-certified smoke generators[2]. To account for variability in technology user results, a minimum of four (4) independent technology users must apply the candidate software to determine the visible opacity of all three hundred

(300) images. For the photographic computer software opacity analysis system to be considered for regulatory certification, the aggregate opacity results generated by each technology user must match the actual visible opacity levels with an average margin of error not to exceed 2.5%.

Photographs employed for software certification, which shall include plumes having visible opacity in the range of zero (0) to sixty (60) percent, shall be issued by a regulatorially approved certifying organization in random order. The administering of certification tests as well as the compilation and documentation of test results shall be conducted under the auspices of the US Environmental Protection Agency's (EPA) Environmental Technology Verification (ETV) program[8]. The ETV program develops testing protocols and verifies the performance of innovative technologies that have the potential to improve protection of human health and the environment. Results of the photographic computer software system certification testing shall be provided to the owner/operator of the computer technology by the ETV program office immediately following documentation of system performance.

For photographic computer software systems that pass certification testing, the technology certification shall be valid for five (5) years assuming that there is no change in software design or functionality. After five years (or sooner in the case where there has been a significant change in the computer software design and/or functionality), the technology qualification procedure must be repeated to retain certification.

3.1.2 Camera Hardware. To certify a given camera for use with a regulatorially approved computer software opacity analysis system, the camera must be able to generate photographs of one hundred fifty (150) black and one hundred fifty (150) white plumes of varying opacity from either a EPA-certified smoke generator or a set of regulatorially approved and standardized plume photographs, which, when analyzed by a valid software package, determines plume opacity with an average margin of error not to exceed 2.5%. Beyond meeting the accuracy standard, cameras employed in support of the present method must be capable of taking and storing fifteen (15) photographic plume images at a rate of at least one image per thirty (30) seconds.

3.2 Certification Procedure.

3.2.1 Software Package. The certification test consists of challenging the candidate computer software opacity analysis system with regulatorially standardized smoke plume photographs. During software certification testing, the visible opacity associated with a set of three hundred (300) standard photographs consisting of one hundred fifty (150) black and one hundred fifty (150) white plumes of varying opacity, shall be determined. To account for variability in technology user results, a minimum of four (4) independent technology users must apply the candidate software to determine the visible opacity of all three hundred (300) images. For the photographic computer software opacity analysis system to be considered for regulatory certification, the aggregate opacity results generated by each technology user must match the actual visible opacity levels with an average margin of error not to exceed 2.5%.

The smoke plumes, which shall be limited to an opacity range of zero (0) to sixty (60) percent, shall be produced using smoke generators equipped with an EPA-certified in-stack transmissometer. Plume photographs employed for software certification shall be issued in random order by the regulatorially approved certification testing organization. Certification photographs shall be issued and quantitative testing results compiled by regulatory approved opacity technology testing organizations administered by the US Environmental Protection Agency's (EPA) Environmental Technology Verification (ETV) program[8]. Results of the computer software opacity analysis system certification testing shall be provided to the owner/operator of the candidate computer technology and all other interested parties by the ETV program office immediately following documentation of system performance.

For photographic computer software systems that pass certification testing, the technology certification shall be valid for five (5) years assuming that there is no change in computer software design or functionality. After five years (or sooner in the case where there has been a significant change in the computer software design and/or functionality), the technology qualification procedure must be repeated to retain certification.

Each set of one hundred fifty (150) black and one hundred fifty (150) white photographs of variable opacity shall be issued to the photographic computer software system in a random order established by ETV or their contractor representatives. During certification testing, the photographic computer software system must assign an opacity value to each plume photograph. To account for variability in technology user results, a minimum of four (4) independent technology users must apply the candidate software to determine the visible opacity of all three hundred (300) images. At the completion of each run of three hundred (300) opacity evaluations, the **average opacity difference** between the photographic computer software system measurements and those reported by the EPA-certified in-stack transmissometer is computed and compared to the established margin of error of 2.5%. The average difference is computed by determining the individual opacity difference between the opacity recorded by the photographic computer software system and that recorded by the EPA-certified in-stack transmissometer for each of the three hundred (300) opacity evaluations. The sum of the individual average differences is then divided by three hundred (300) to determine the **average opacity difference**. If any photographic computer software system fails to qualify, ETV (or its contractor representatives) may re-issue a complete set of three hundred (300) photographs of regulatorially approved standard black and white smoke plumes in a retest of the computer software. The results of any retest shall be provided to the owner/operator of the candidate computer technology and all other interested parties by the ETV program office immediately following documentation of system performance.

3.2.2 Camera Hardware. The camera certification test consists of challenging the candidate camera hardware to generate three hundred (300) photographs consisting of one hundred fifty (150) black and one hundred fifty (150) white plumes of varying opacity from either: 1) observing the visible emissions from an EPA-certified smoke generator or by 2) photographing an existing set of three hundred (300) regulatorially standard plume photographs.

If camera performance is to be established by use of an EPA-certified smoke generator, photographs of the visible emissions shall be taken at a distance sufficient to provide a clear view of the plume with the sun oriented in the 140º sector to the photographer’s back. Photographs shall be taken from a position such that the camera’s line of vision is approximately perpendicular to the plume direction. Enhanced focus of the visible emissions through use of an optical and/or digital zoom feature may be employed.

Once certification photographs have been compiled, each shall be analyzed by using a regulatorially valid computer software opacity analysis system by a minimum of four (4) independent technology users. In the case where a smoke generator is employed, the candidate camera hardware shall be considered certified if the resulting opacity readings match the opacity values recorded by the EPA-certified smoke generator with an average margin of error not to exceed 2.5%. Where the candidate camera hardware is employed to record images of a set of three hundred (300) regulatorially approved standard plume photographs, the camera hardware shall be considered certified if the resulting opacity readings determined by a minimum of four (4) independent technology users match the known opacity values with an average margin of error not to exceed 2.5%.

When the accuracy standard established for certifying camera hardware is achieved, the camera *meta* data shall be recorded and retained in the certification documentation. Identical camera settings shall be employed during any subsequent field measurements with the certified camera hardware.

4.0 References (Appendix B).

1. *Federal Register* (1971) “Method 9—Visual Determination of the Opacity of Emissions from Stationary Sources,” vol. 36 No. 247 December 23.

2. US Environmental Protection Agency (1975) *Evaluation and Collaborative Study of Method for Visual Determination of Opacity of Emissions from Stationary Sources* Contract No. 68-02-0626.

3. Environmental Security Technology Certification Program (2005) *An Alternative to EPA Method 9—Field Validation of the Digital Opacity Compliance System (DOCS)* Final Report Project No. CP-200119 May.

4. Environmental Security Technology Certification Program (2005) *An Alternative to EPA Method 9—Field Validation of the Digital Opacity Compliance System (DOCS)* Cost and Performance Report: Project No. CP-200119 February.

5. McFarland, M. J., Stone, D.A., Calidonna, M. J., Rasmussen, S. L., and S. H. Terry (2003) “Evaluation of the Digital Opacity Compliance System (DOCS) in High Mountain Desert Environment” *Journal of the Air and Waste Management Association* vol. 53 pp 724–730.

6. McFarland, M. J., Stone, D.A., Calidonna, M. J., Kerch, P.E., Rasmussen, S. L. and S.H. Terry, (2004) “Measuring Visual Opacity Using Digital Imaging Technology” *Journal of the Air & Waste Management Association* vol. 54 pp. 296–306.

7 McFarland, M. J., Stone, D.A., Rasmussen, S. L., Calidonna, M. J., Kerch, P.E., and J. A. Gunter (2004) “Evaluation of the Digital Opacity Compliance System (DOCS) at Military and Commercial Industrial Sites,” *Federal Facilities Environmental Journal* vol. 15, Issue 2 pp. 73–81.

8. U.S. Environmental Protection Agency – Environmental Technology Verification (ETV) Program – URL: http://www.epa.gov/etv/